

(19) World Intellectual Property Organization  
International Bureau



(43) International Publication Date  
31 January 2002 (31.01.2002)

PCT

(10) International Publication Number  
**WO 02/09268 A1**

(51) International Patent Classification<sup>7</sup>: **H03B 1/00**,  
H03K 5/00

(21) International Application Number: PCT/US01/23314

(22) International Filing Date: 23 July 2001 (23.07.2001)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:  
60/220,050 21 July 2000 (21.07.2000) US

(71) Applicant: **IXYS CORPORATION** [US/US]; 3540 Bas-  
sett Street, Santa Clara, CA 95054 (US).

(72) Inventor: **OCHI, Sam**; 19920 Saraglen Court, Saratoga,  
CA 95070 (US).

(81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, UZ, VN, YU, ZA, ZW.

(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

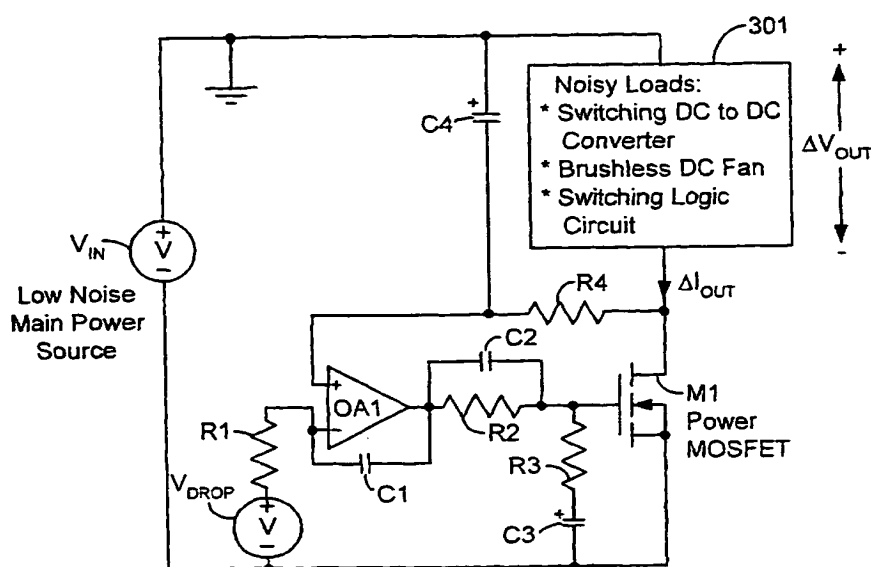
Published:

— with international search report

(74) Agents: **SMITH, Slade, E. et al.**; Townsend and  
Townsend and Crew LLP, Two Embarcadero Center, 8th  
Floor, San Francisco, CA 94111-3834 (US).

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: ACTIVE POWER FILTER FOR ISOLATING ELECTRICALLY NOISY LOAD FROM LOW NOISE POWER SUPPLY



(57) Abstract: An active power filter includes a feedback resistor (R4) and a shunt capacitor (C4), an operational amplifier equivalent subcircuit (ideal equivalent OA), and a voltage drop source (Vdrop). The shunt capacitor connects the positive terminals of the low noise power supply (Vin) and the noisy load (401) to the positive terminal of the operational amplifier equivalent subcircuit. The feedback resistor connects the negative terminal of the noisy load and the output of the operational amplifier equivalent subcircuit to the negative terminal of the shunt capacitor. The voltage drop source connects the negative terminal of the low noise power supply to the negative terminal of the operational amplifier equivalent subcircuit. The operational equivalent subcircuit

includes an operational amplifier (OA1), three resistors (R1-R3), three capacitors (C1-C3), and a transistor (M1). The first resistor (R1) connects the positive terminal of the voltage drop source to the negative input terminal of the operational amplifier. The second resistor (R2) connects the output of the operational amplifier to the gate of the transistor. The drain of the transistor is coupled to the negative terminal of the noisy load. The source of the transistor is coupled to the negative terminal of the voltage drop source and to the negative terminal of the low noise direct current power supply. The first capacitor connects the output of the operational amplifier to the negative input terminal of the operational amplifier. The third capacitor (C3) and a third resistor (R3) are connected in series between the gate of the transistor and the negative terminal of the low noise direct current power supply.

WO 02/09268 A1

## ACTIVE POWER FILTER FOR ISOLATING ELECTRICALLY NOISY LOAD FROM LOW NOISE POWER SUPPLY

### 5 CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority from U.S. Provisional Application No. 60/220,050, entitled "Active Power Filter Invention", filed July 21, 2000, which is herein incorporated by reference in its entirety for all purposes.

### 10 BACKGROUND OF THE INVENTION

#### 1. FIELD OF THE INVENTION

The present invention relates to the field of supplying direct current (DC) power; and specifically, to filtering noise between the power supply and the load driven by the power supply.

#### 15 2. DISCUSSION OF THE RELATED ART

Figure 1 illustrates a conventional filter for isolating an electrically noisy load from a low noise main power supply source. The conventional circuit illustrated in Figure 1 is used primarily to filter an electrically noisy load 101 such as a switching DC to DC converter, brushless DC motor, switching logic circuit, or another noisy direct current powered circuit from a low noise main power source,  $V_{IN}$ . Inductor L1 acts as a passive low pass filter for isolating a low noise main power source,  $V_{IN}$ , from noise generated by the noisy load.

The inductance value of inductor L1 is chosen to optimize the noise filtering requirements. In designing the a conventional circuit such as illustrated in Figure 1, care must be exercised in the choice and physical placement of inductor L1 as it may emit magnetic noise interference, and it may be physically large. Magnetic noise interference may undesirably affect the performance of the load device, the power supply, and other unrelated electronic/magnetic devices in the physically nearby area of the system illustrated in Figure 1.

### SUMMARY OF THE INVENTION

30 An object of the present invention is to create an active power filter which behaves like a filter circuit having a large inductor, but without producing magnetic interference or physically large components as would be produced by a conventional large inductor. The

power filter according to the present invention is suitable for use with switching DC to DC converters, brushless DC fans, switching logic circuits, and other noisy loads.

According to the present invention, an active power filter includes a feedback resistor and a shunt capacitor, an operational amplifier equivalent subcircuit, and a voltage drop source. The shunt capacitor connects the positive terminals of the low noise power supply and the noisy load to the positive terminal of the operational amplifier equivalent subcircuit. The feed back resistor connects the negative terminal of the noisy load and the output of the operational amplifier equivalent subcircuit to the negative terminal of the shunt capacitor. The voltage drop source connects the negative terminal of the low noise power supply to the negative terminal of the operational amplifier equivalent subcircuit.

According to the present invention, the impedance of the active power filter at a minimum noise frequency is carefully designed so as to be large in comparison to an impedance of the noisy load, for example, the impedance of the active power filter is 1000 times the impedance of the noisy load at the minimum noise frequency. The active power filter according to the present invention is equally capable of protecting a low noise load device to a noisy direct current power supply.

According to another aspect of the present invention, the operational equivalent subcircuit includes an operational amplifier, first and second resistors, and a transistor. The first resistor connects the positive terminal of the voltage drop source to the negative input terminal of the operational amplifier. The second resistor connects the output of the operational amplifier to the gate of the transistor. The drain of the transistor is coupled to the negative terminal of the noisy load. The source of the transistor is coupled to the negative terminal of the voltage drop source and to the negative terminal of the low noise direct current power supply. The positive input terminal of the operational amplifier forms the positive input terminal of the operational amplifier equivalent subcircuit.

In an exemplary embodiment of the active power filter according to the present invention, the operational amplifier equivalent subcircuit further includes, first and second capacitors. The first capacitor connects the output of the operational amplifier to the negative input terminal of the operational amplifier. The second capacitor connects the output of the operational amplifier to the gate of the transistor. In addition, the operational amplifier equivalent subcircuit may contain a third capacitor and a third resistor which are connected in series between the gate of the transistor and the negative terminal of the low noise direct current power supply. In an exemplary embodiment, the transistor comprises an N-channel enhancement mode MOS field effect transistor.

These and other features, aspects, and advantages of the present invention are more fully described in the Detailed Description of the Invention with reference to the Figures.

### BRIEF DESCRIPTION OF THE DRAWINGS

5 Figure 1 illustrates a conventional filter for isolating an electrically noisy load from a low noise main power supply source.

Figure 2 illustrates an exemplary load noise generated at the power terminals of the noisy load by the noisy load.

10 Figure 3 illustrates an active power filter according to the present invention for isolating an electrically noisy load from a low noise main power supply source.

Figure 4 illustrates a simplified circuit according to the present invention of the active power filter for isolating an electrically noisy load.

Figure 5 illustrates an equivalent subcircuit for the active inductor circuit according to the present invention for isolating an electrically noisy load.

15 The Figures are more thoroughly explained in the Detailed Description of the Invention.

### DETAILED DESCRIPTION OF THE INVENTION

20 Figure 2 illustrates an exemplary load noise,  $\Delta V_{OUT}$ , that the noisy load 101 generates at its power terminals. As an example, the noisy load 101 may be a 10 Amp DC load with 1 Amp AC (alternating current),  $\Delta I_{OUT}$ , of noise with approximately 1 V PP (peak-to-peak), and with spectral frequency components as low as 20 Hz, such as illustrated in Figure 2. The dynamic load impedance can be expressed as the following Equation 1.

$$Z_{LOAD} = \Delta V_{OUT} / \Delta I_{OUT} \quad (\text{Equation 1})$$

25 To maintain low noise for the main power source,  $V_{IN}$ , the inductor L1 in Figure 1 should be sized with a high impedance relative to the impedance,  $Z_{LOAD}$ , of the noisy load 101, such as  $Z_{L1} \sim 1000 * Z_{LOAD}$ . This will minimize the affects that the noise in Figure 2 has on the low noise power supply  $V_{IN}$ . An equivalent resistance,  $Z_{LOAD}$ , of the noisy load 101 for the given conditions from Equation 1 is shown below.

30 
$$Z_{LOAD} = (1VPP) / (1Amp) = 1 \text{ Ohm.}$$

An expression for the impedance of inductor L1 in Figure 1 is shown below as Equation 2.

$$Z_{L1} = 2\pi * f * L1 \quad (\text{Equation 2})$$

Since the minimum noise frequency  $f_{\min}$  is 20Hz in the example of Figure 2, and since the desired inductor L1 impedance is 1000 Ohms in this example, rearranging Equation 2 to solve for the inductance L1, the following results.

$$L1 = 1000 \text{ Ohms} / (2\pi * 20\text{Hz}) \approx 8 \text{ Henrys}$$

5 A practical inductor L1 having this value of 8 Henries would weigh greater than 10 pounds and would have a significant physical size.

Figure 3 illustrates an active power filter according to the present invention for isolating an electrically noisy load 301 from a low noise main power supply source,  $V_{IN}$ .

The active power filter circuit in Figure 3 according to the present invention serves  
10 the same function as the conventional one in Figure 1 without the need for an inductor. The components transistor M1, resistor R1, resistor R2, resistor R3, feedback resistor R4, capacitor C1, capacitor C2, capacitor C3, and shunt capacitor C4 with respect to operational amplifier OA1 form an active inductor. The transistor M1 is implemented, for example, by such as an enhancement mode N-channel MOS field effect transistor. The voltage source  
15  $V_{DROP}$  serves to provide the necessary headroom for the active circuitry to properly function.

Figure 4 illustrates a simplified circuit according to the present invention of the active power filter for isolating an electrically noisy load. To understand the functioning of the present invention, the components resistor R1, resistor R2, resistor R3, capacitor C1, capacitor C2, capacitor C3, and transistor M1 can be included into an idealized operational  
20 amplifier OA as shown in Figure 4, with only shunt capacitor C4 and feedback resistor R4 remaining along with voltage source  $V_{DROP}$ , and low noise power supply  $V_{IN}$ , from among the circuit elements shown in Figure 3. From Figure 4, a frequency,  $f_{VOUT}(-3\text{db})$  is defined, in which the impedance of shunt capacitor C4 is equal in magnitude to the impedance of feedback resistor R4. At  $f_{VOUT}(-3\text{db})$ ,  $\frac{1}{2} \Delta V_{OUT}$  is dropped across feedback resistor R4 and the  
25 other  $\frac{1}{2} \Delta V_{OUT}$  across shunt capacitor C4. In other words, at the frequency  $f_{VOUT}(-3\text{db})$ , the circuit impedance of the Figure 4 combination of elements seen by the noisy load 401 is equal to the dynamic load impedance of the noisy load 401 itself.

Consequently, the total impedance at this frequency  $f_{VOUT}(-3\text{db})$  seen by low noise power source  $V_{IN}$  is  $2 * \Delta V_{OUT} / \Delta I_{OUT}$  or 2 times the dynamic load impedance of the noisy  
30 load 401. An expression for  $f_{VOUT}(-3\text{db})$  is given below as Equation 3.

$$f_{VOUT}(-3\text{db}) = 1 / (2\pi R4 * C4) \quad (\text{Equation 3})$$

An expression for the impedance for an inductor is given below as Equation 4.

$$Z_L = 2\pi f * L \quad (\text{Equation 4})$$

Figure 5 illustrates an equivalent circuit for the active inductor circuit according to the present invention for isolating an electrically noisy load 501. At  $f_{V_{OUT}}(-3\text{db})$ , and solving Equation 4 for L, an expression for the equivalent inductor,  $L_{EQUV}$  is given below as

5 Equation 5.

$$L_{EQUV} = Z_{LEQUV} / \{2\pi * f_{V_{OUT}}(-3\text{db})\} \quad (\text{Equation 5})$$

Using the expression for  $f_{V_{OUT}}(-3\text{db})$  from Equation 3, since  $Z_{LEQUV} = Z_{LOAD}$  at this frequency, and using the expression for  $Z_{LOAD}$  from Equation 1, Equation 5 simplifies to the following equation 6.

$$10 \quad L_{EQUV} = R_4 * C_4 * \Delta V_{OUT} / \Delta I_{OUT} \quad (\text{Equation 6})$$

A circuit showing the use of equivalent inductor  $L_{EQUV}$  is given in Figure 5. Voltage source  $V_{DROP}$  can be set to be  $I_{OUTDC} * R_{SERIES}$ , where  $I_{OUTDC}$  is the average DC operating current of the load and  $R_{SERIES}$  is the DC resistance of inductor L1 such as in Figure 1.

As a comparison, substituting the conventional example requirement of  $L1 = 8$   
 15 Henrys from Figure 1 into the active power filter according to the present invention, so that  $L_{EQUV} = 8$  Henrys, and  $\Delta V_{OUT} = 1\text{VPP}$ ,  $\Delta I_{OUT} = 1\text{Amp R.M.S}$  (root mean square) in Figure 5, from Equation 6,

$$L_{EQUV} = 8\text{H} = R_4 * C_4 * 1\text{V} / 1\text{A} = R_4 * C_4.$$

By selecting  $R_4 = 1\text{Megaohm}$ , and solving for  $C_4$ ,  $C_4 = 8\text{H} / 1\text{Megaohm} = 8\text{uF}$ .

20 While the present invention has been described with reference to its exemplary embodiment, that embodiment is offered by way of example, not by way of limitation. Those of ordinary skill in the art will be enabled by this disclosure to add to or modify the embodiments of the present invention in various ways. For example, the nominal resistances, capacitances, inductances, and load and noise characteristics described above are only  
 25 exemplary values, and are by no means restrictive. In addition, although the active power filter has been described as protecting a low noise power supply from a noisy load device, it is to be noted that the the active power filter according to the present invention is equally capable of protecting a low noise load device from a noisy power supply. Accordingly, those additions and modifications are deemed to lie within the spirit and scope of the present  
 30 invention, as delineated by the appended claims.

## WHAT IS CLAIMED IS:

1. An active power filter, comprising:
  - a feedback resistor having first and second terminals;
  - 5 a shunt capacitor having positive and negative terminals;
  - an operational amplifier equivalent subcircuit having positive and negative input terminals and having an output terminal; and
  - a voltage drop source having positive and negative terminals;
  - wherein the positive terminal of the shunt capacitor is coupled to a positive terminal
  - 10 of a noisy load device and to a positive terminal of a low noise direct current power supply;
  - wherein the negative terminal of the shunt capacitor is coupled to the second terminal of the feedback resistor and to the positive input terminal of the operational amplifier equivalent subcircuit;
  - wherein the first terminal of the feedback resistor is coupled to the negative terminal
  - 15 of the noisy load device and to the output terminal of the operational amplifier equivalent subcircuit;
  - wherein the positive terminal of the voltage drop source is coupled to the negative terminal of the operational amplifier equivalent subcircuit;
  - wherein the negative terminal of the voltage drop source is coupled to a negative
  - 20 terminal of the low noise direct current power supply.
2. An active power filter as in claim 1, wherein the operational amplifier equivalent subcircuit comprises:
  - an operational amplifier having positive and negative input terminals and having an
  - 25 output terminal;
  - a first resistor having first and second terminals;
  - a second resistor having first and second terminals; and
  - a transistor having a gate, a source, and a drain;
  - wherein the positive input terminal of the operational amplifier forms the positive
  - 30 input terminal of the operational amplifier equivalent subcircuit;
  - wherein the drain of the transistor forms the output terminal of the operational amplifier equivalent subcircuit;
  - wherein the first terminal of the first resistor is coupled to the negative terminal of the operational amplifier;

wherein the second terminal of the first resistor forms the negative terminal of the operational amplifier equivalent subcircuit;

wherein the first terminal of the second resistor is coupled to the gate of the transistor;  
and

5 wherein the second terminal of the second resistor is coupled to output terminal of the operational amplifier.

3. An active power filter as in claim 2,

10 wherein the source of the transistor is coupled to the negative terminal of the voltage drop source.

4. An active power filter as in claim 2, wherein the operational amplifier equivalent subcircuit further includes:

a first capacitor having first and second terminals;

15 wherein the first terminal of the first capacitor is coupled to the output terminal of the operational amplifier; and

wherein the second terminal of the first capacitor is coupled to the negative input terminal of the operational amplifier.

20 5. An active power filter as in claim 4, wherein the operational amplifier equivalent subcircuit further includes:

a second capacitor having first and second terminals;

wherein the first terminal of the second capacitor is coupled to the gate of the transistor; and

25 wherein the second terminal of the second capacitor is coupled to the output terminal of the operational amplifier.

6. An active power filter as in claim 5, wherein the operational amplifier equivalent subcircuit further includes:

30 a third capacitor; and

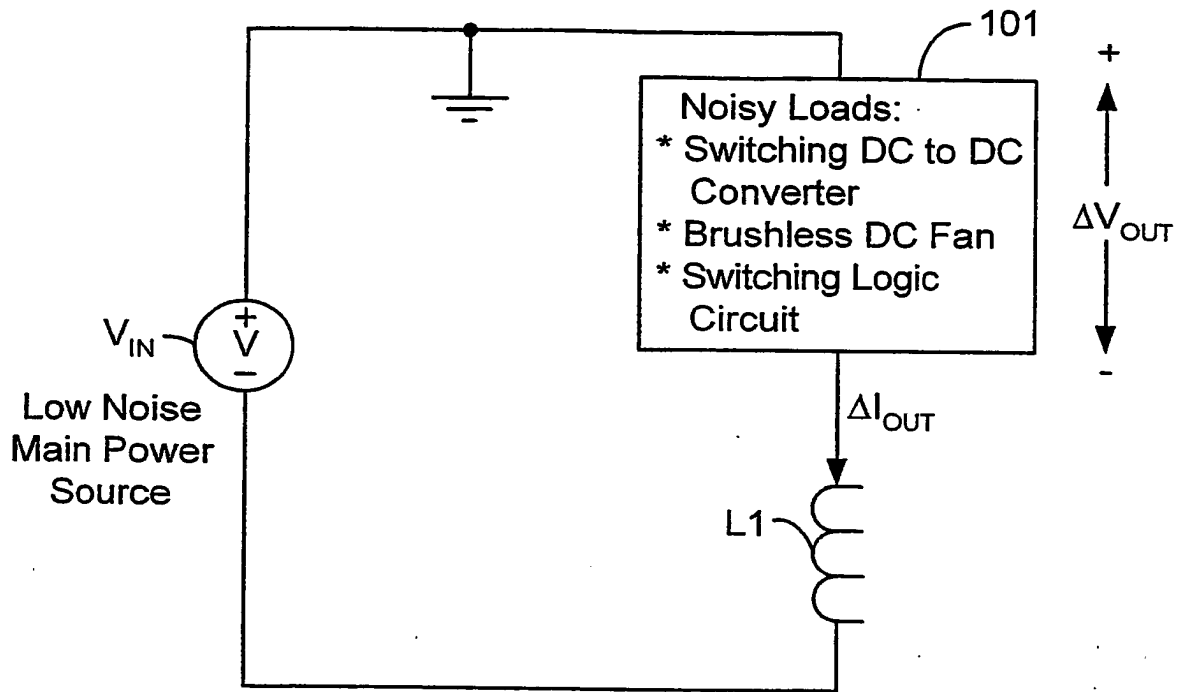
a third resistor;

wherein the third capacitor and the third resistor are connected in series between the gate of the transistor and the negative terminal of the voltage drop source.

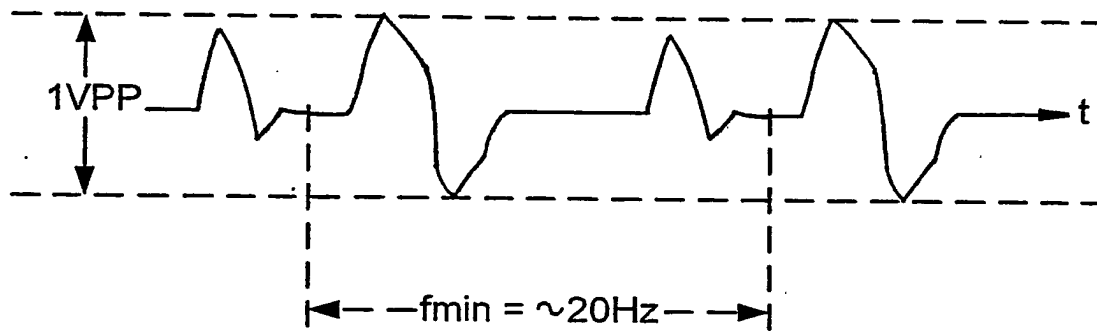


7. An active power filter as in claim 2, wherein the transistor comprises an N-channel enhancement mode MOS field effect transistor.
8. An active power filter as in claim 1, wherein the noisy load comprises a switching DC to DC converter.
9. An active power filter as in claim 1, wherein the noisy load comprises a brushless DC fan.
10. An active power filter as in claim 1, wherein the noisy load comprises a switching logic circuit.
11. An active power filter as in claim 1,  
wherein an impedance of the active power filter is large in comparison to an  
impedance of the noisy load at a minimum noise frequency generated by the noisy load.
12. An active power filter, comprising:  
a feedback resistor having first and second terminals;  
a shunt capacitor having positive and negative terminals;  
an operational amplifier equivalent subcircuit having positive and negative input  
terminals and having an output terminal; and  
a voltage drop source having positive and negative terminals;  
wherein the positive terminal of the shunt capacitor is coupled to a positive terminal  
of a low noise load device and to a positive terminal of a noisy direct current power supply;  
wherein the negative terminal of the shunt capacitor is coupled to the second terminal  
of the feedback resistor and to the positive input terminal of the operational amplifier  
equivalent subcircuit;  
wherein the first terminal of the feedback resistor is coupled to the negative terminal  
of the low noise load device and to the output terminal of the operational amplifier equivalent  
subcircuit;  
wherein the positive terminal of the voltage drop source is coupled to the negative  
terminal of the operational amplifier equivalent subcircuit;  
wherein the negative terminal of the voltage drop source is coupled to a negative  
terminal of the noisy direct current power supply.

1/3



**FIG. 1.** (PRIOR ART)



**FIG. 2.**

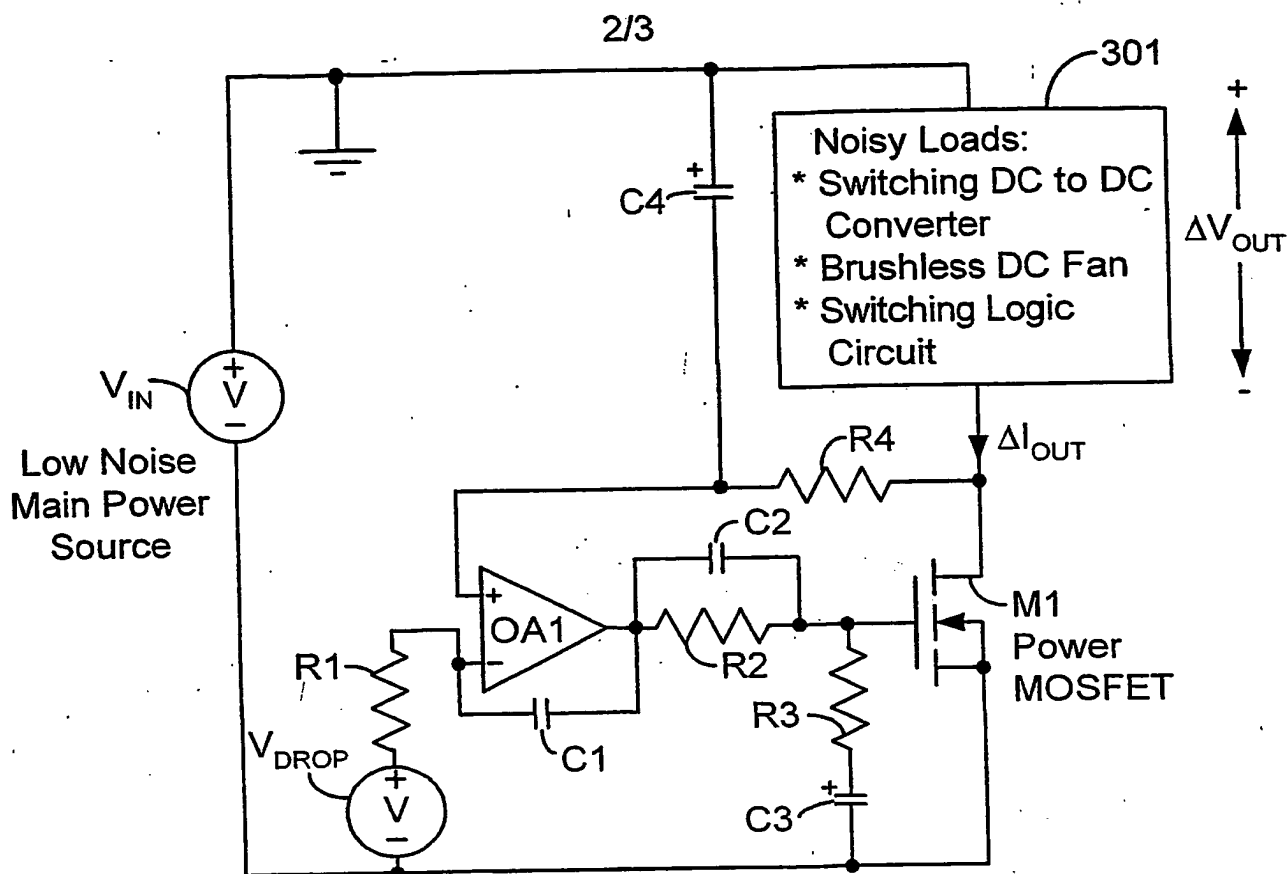


FIG. 3.

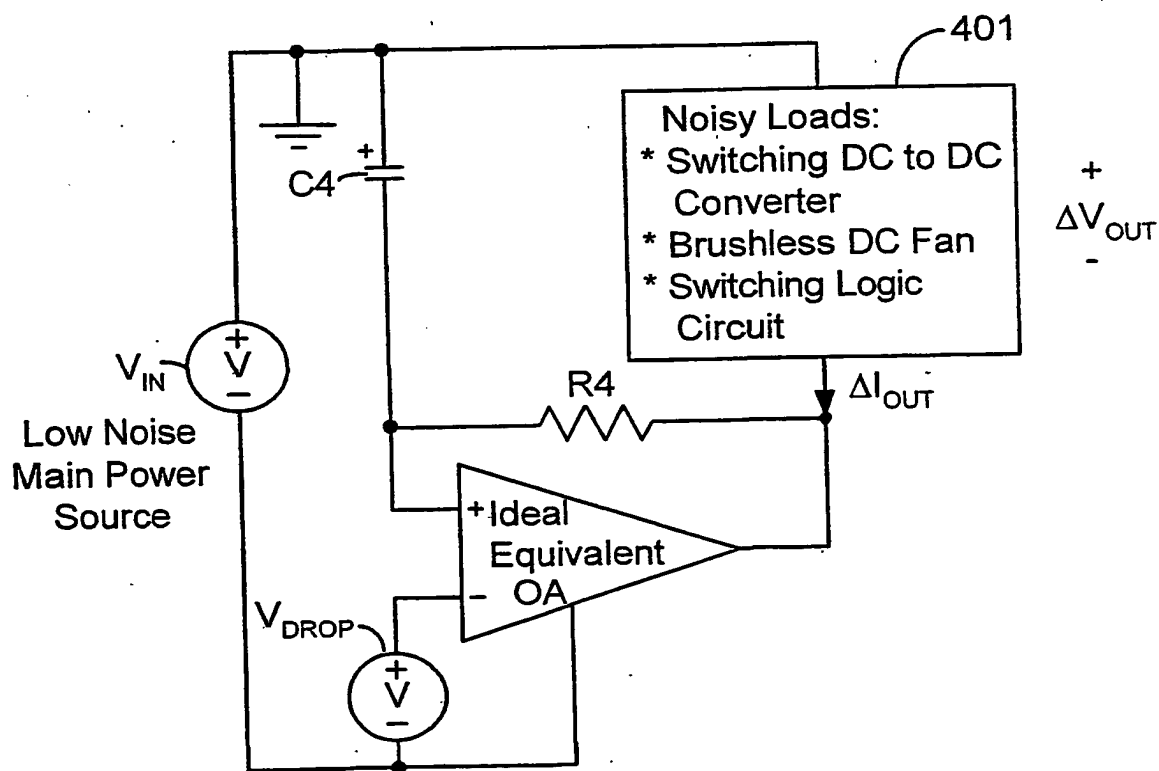


FIG. 4.

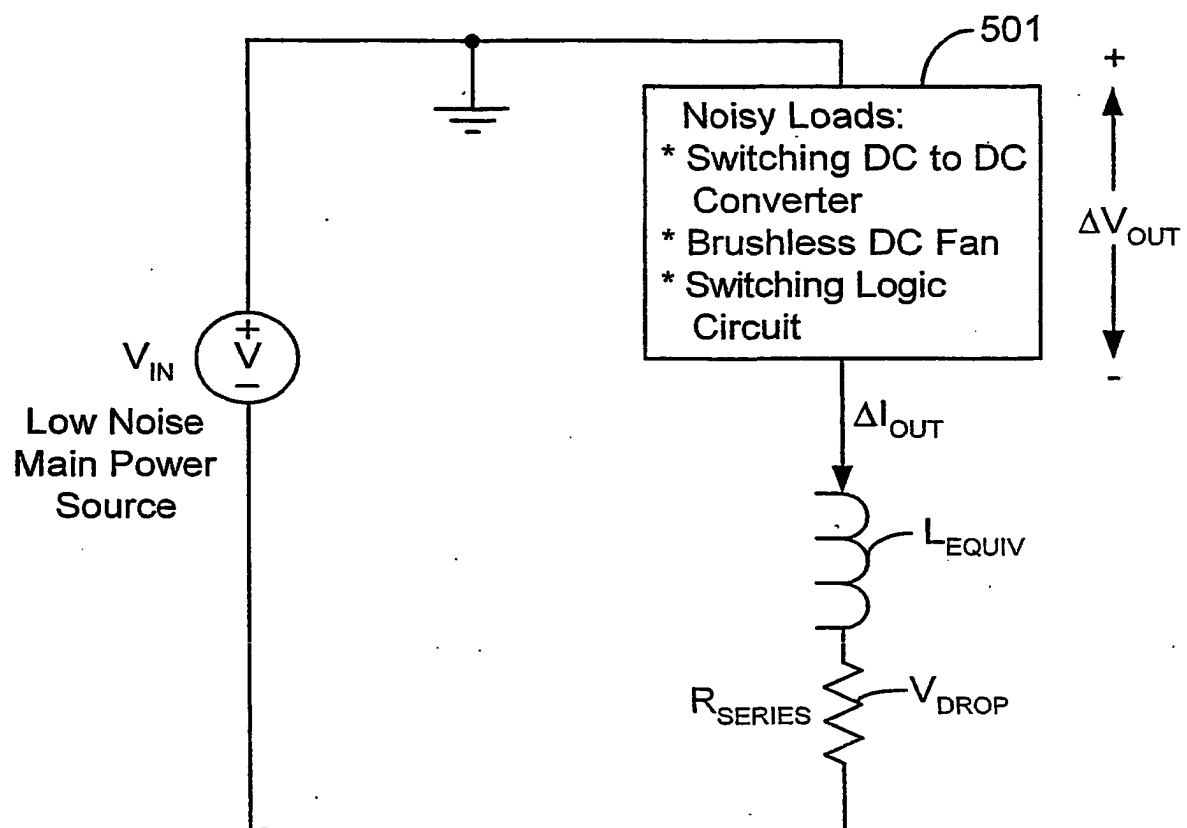


FIG. 5.

# INTERNATIONAL SEARCH REPORT

International application No.

PCT/US01/23314

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : H03B 1/00; H03K 5/00

US CL : 327/551

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 327/427, 551-559

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)  
USPTO EAST

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X + A	US 4,078,205 A (Van Schoiack) 07 March 1978, (07/03/78) figure 3	1, 12 2-11

☐ Further documents are listed in the continuation of Box C.

☐ See patent family annex.

\* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

26 September 2001 (26.09.2001)

Date of mailing of the international search report

18 OCT 2001

Name and mailing address of the ISA/US

Commissioner of Patents and Trademarks  
Box PCT  
Washington, D.C. 20231

Facsimile No. (703)305-3230

Authorized officer

Quan Tran Macaluso

Telephone No. 703-308-0956

Form PCT/ISA/210 (second sheet) (July 1998)

**THIS PAGE BLANK (USPTO)**